論文 / 著書情報
Article / Book Information

論題(和文)	
Title(English)	Digital feedback system for active spin maser
著者(和文)	小島修一郎, 佐藤智哉, 市川雄一, 大友祐一, 坂本雄, 鈴木貴大, 近森正敏, 彦田絵里, 宮武裕和, 七尾翼, 鈴木都文, 土屋真人, 井上壮志, 古川武, 吉見 彰洋, BIDINOSTI Christopher, 猪野 隆, 上野秀樹, 松尾由賀利, 福山武志, 旭耕一郎
Authors(English)	Shuchirou Kojima, Tomoya Sato, Yuichi Ichikawa, Yuichi Ohtomo, Yu Sakamoto, Takahiro Suzuki, Masatoshi Chikamori, Eri Hikota, Hirokazu Miyatake, Tsubasa Nanao, Kunifumi Suzuki, Masato Tsuchiya, Takeshi Inoue, Takeshi Furukawa, Akihiro Yoshimi, Christopher Bidinosti, Takashi Ino, Hideki Ueno, Yukari Matsuo, Takeshi Fukuyama, KOICHIRO ASAHI
出典(和文)	, , , pp. 92-95
Citation(English)	Proceedings of 7th International Workshop on Fundamental Physics Using Atoms (FPUA2014), , , pp. 92-95
発行日 / Pub. date	2015, 1

Digital feedback system for active spin maser

S. Kojima[a,*], T. Sato[a], Y. Ichikawa[a,b], Y. Ohtomo[a], Y. Sakamoto[a], T. Suzuki[a], M. Chikamori[a], E. Hikota[a], H. Miyatake[a], T. Nanao[a], K. Suzuki[a], M. Tsuchiya[a], T. Inoue[c], T. Furukawa[d], A. Yoshimi[e], C. P. Bidinosti[f], T. Ino[g], H. Ueno[b], Y. Matsuo[h], T. Fukuyama[i], K. Asahi[a]

[a]*Department of Physics, Tokyo Institute of Technology, 2-12-1 Oh-okayama, Meguro, Tokyo 152-8551, Japan*
[b]*RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[c]*Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba, Sendai 980-8578, Japan*
[d]*Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan*
[e]*Research Core for Extreme Quantum World, Okayama University, 3-1-1 Tsushimanaka, Kita, Okayama 700-8530, Japan*
[f]*Department of Physics, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, Canada*
[g]*Institute of Material Structure Science, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[h]*Department of Advanced Sciences, Hosei University, 3-7-2 Kajino-cho, Koganei, Tokyo 184-8584, Japan*
[i]*Research Center for Nuclear Physics (RCNP), Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*

Abstract

Experimental search for an electric dipole moment in diamagnetic atom ^{129}Xe through precision measurement of spin precession frequency using an active nuclear spin maser is in progress. In the active spin maser system, the frequency shift due to the phase error of the artificial feedback field (pulling effect) may give rise to the systematic uncertainty. In order to reduce the pulling effect, new procedure to determine the phase of precession was introduced and new system to produce digitalized feedback signals was developed. The active maser employing the new procedure and the digital feedback system has been successfully operated.

1. Introduction

A permanent electric dipole moment (EDM) of a particle, atom, or molecule is an observable directly violating the time reversal symmetry, and is sensitive to CP-violating phases beyond the framework of the Standard Model of elementary particles. The aim of our EDM study is to measure the EDM in a diamagnetic atom ^{129}Xe at a level of $|d| = 10^{-28}$ $e$cm beyond the current upper limit [1]. The EDM measurement is to be done through observation of a difference in the spin precession frequency between two experimental configurations with the electric field applied parallel and antiparallel to the static magnet field. The EDM search to a sensitivity of $|d| = 10^{-28}$ $e$cm requires a frequency precision of 1 nHz or better under an electric field of 10 kV/cm.

In order to achieve such a high frequency precision, a technique of an active nuclear spin maser [2, 3] is employed in our EDM study. The active spin maser operates as follows. A glass cell enclosing ^{129}Xe gas is located in an applied static field $B_0 \sim 30$ mG. The ^{129}Xe spin is longitudinally polarized through spin exchange with polarized Rb atoms which are optically pumped. The ^{129}Xe precession is detected optically through re-polarization of Rb atoms by the ^{129}Xe spin. The feedback (FB) system generates a rotating magnetic field $\boldsymbol{B}_{\mathrm{FB}}$ from the precession signal. The $\boldsymbol{B}_{\mathrm{FB}}$ phase is adjusted by a phase shifter such that the $\boldsymbol{B}_{\mathrm{FB}}$ direction is kept orthogonal to the instantaneous direction of the transverse component of ^{129}Xe magnetization. The $\boldsymbol{B}_{\mathrm{FB}}$ thus prevents the ^{129}Xe spin from transverse spin relaxation. In this way, the spin maser maintains the precession semipermanently. Previous development in the spin maser has achieved a precision $\delta\nu = 9.3$ nHz for the averaged frequency in a continued precession for 3×10^4 s [3, 4].

The FB system in the current maser system consists of four circuits. Polarization of the probe laser is modulated at 50 kHz by a photoelastic modulator (PEM). A Lock-in Amplifier (PEM-LA) removes the PEM modulation and amplifies the ^{129}Xe precession signal $V_0 \cos(\omega_0 t + \theta_0)$ by referring to the frequency of the PEM modulation. Another

*Corresponding author
Email address: `kojima.s@yap.nucl.ap.titech.ac.jp` (S. Kojima)

Lock-in Amplifier (Xe-LA) modulates the precession signal with an oscillation frequency $\omega_{\rm ref}$ provided by a function generator, yielding two signals $V_x(t) = V_0\cos(\omega_0 t + \theta_0)\cos(\omega_{\rm ref} t + \theta_{\rm ref})$ and $V_y(t) = V_0\cos(\omega_0 t + \theta_0)\sin(\omega_{\rm ref} t + \theta_{\rm ref})$. They are then passed through a low pass filter, and as a result two beat signals $\overline{V}_x(t) = V_0\cos[(\omega_0 - \omega_{\rm ref})t + (\theta_0 - \theta_{\rm ref})]$ and $\overline{V}_y(t) = V_0\sin[(\omega_0 - \omega_{\rm ref})t + (\theta_0 - \theta_{\rm ref})]$ are obtained. The reference frequency $\omega_{\rm ref}$ is chosen close to ω_0 in order to allow the Xe-LA to cut noises off the precession signal. In the final step, a circuit (FB circuit) demodulates the precession signal by processing the signals as

$$V_{\rm FB}(t) = \overline{V}_x(t) \times \cos(\omega_{\rm ref} t + \theta_{\rm ref}) - \overline{V}_y(t) \times \sin(\omega_{\rm ref} t + \theta_{\rm ref}) = V_0\sin(\omega_0 t + \theta_0). \tag{1}$$

A magnetic field $\boldsymbol{B}_{\rm FB}$ proportional to $V_{\rm FB}(t)$ is generated and applied to the ^{129}Xe spins.

As described above, the FB field is produced artificially in this active spin maser system, where the resultant phase of $\boldsymbol{B}_{\rm FB}$ after the processes in the circuits can be controlled to be orthogonal to the phase of the spin precession by using a phase shifter. When $\boldsymbol{B}_{\rm FB}$ is subject to a phase error δ, the FB system causes unwilling frequency shift, a pulling effect, of $\Delta\nu = \tan\delta/2\pi T_2$, where T_2 is the transverse relaxation time for the ^{129}Xe precession. The effect should be reduced by proper control of $\boldsymbol{B}_{\rm FB}$. The typical size of the pulling effect, under $\delta \sim 1^\circ$ and $T_2 \sim 10$ s, is estimated as $\Delta\nu \sim 2.8 \times 10^2$ μHz. The optimization of the phase is thus important for the EDM measurement.

In the present study, a new procedure to optimize the phase of $\boldsymbol{B}_{\rm FB}$ is proposed in order to reduce the phase error. A new feedback system in which the feedback signal is produced in digital operations, is also developed. The maser operation of ^{129}Xe using the new procedure and digital FB system is reported.

2. Phase shift on the feedback system

In the current FB system, the phase of $\boldsymbol{B}_{\rm FB}$ is optimized through several runs of T_2 measurements. With a $\boldsymbol{B}_{\rm FB}$ having the right phase, the ^{129}Xe precession does not decay. Conversely with $\boldsymbol{B}_{\rm FB}$ having the opposite phase, the ^{129}Xe precession decays even faster than the free induction decay. The phase which gives the shortest T_2 should differ by an angle 180° from the phase appropriate for masing. Therefore, we search for the $\boldsymbol{B}_{\rm FB}$ phase which gives the shortest T_2, and by adding 180° to it we obtain the right phase for the maser operation. In fact, this procedure allows us to determine the phase to a 1° precision in typical.

The above procedure of the phase setting needs to be executed every time the maser is operated, because the optimum $\boldsymbol{B}_{\rm FB}$ phase seems to change unexpectedly for presently unknown reason. The shift of the precession frequency due to the pulling effect thus changes every time that the maser is operated, which might be one of sources of the systematic errors in the present EDM experiment. In order to understand how the precession signal is processed actually, phase shifts appearing in Xe-LA and the analog FB circuit are measured. Figure 1 shows the FB system used for the measurement of the phase shift. The input signal to Xe-LA is processed in a computer in the same way as in the real circuits, and at the same time the output signal is sampled. The computer calculates the difference between the phase of the computer-calculated signal and the output signal from the FB circuit. Figure 2 shows a histogram for the phase difference result. The histogram is fitted with a function of the Cauchy distribution,

$$f(x) = \frac{C}{\pi} \cdot \frac{a}{(x-b)^2 + a^2} \tag{2}$$

where a is the half width at half maximum, b the peak phase difference, and C a scaling factor. As a result of the fitting, $a = (12.582 \pm 0.006)^\circ$, $b = (33.495 \pm 0.004)^\circ$ are obtained. The calculated value does not include other signal delays, mainly on the PEM-LA, and its delay is estimated as 12.4°. The calculated value (33.495 ± 0.004)° agrees with combination value (32.2 ± 0.6)° which is obtained by summing the empirical phase (19.8 ± 0.6)° determined by searching for the shortest T_2 condition and the assumed signal delay 12.4° in PEM-LA. Eventually, the unknown phase shift thus turned out to originate from Xe-LA and the FB circuit, and its value will be controlled within 0.01°. The pulling effect will be reduced down to 2.8 μHz or smaller.

3. Digital feedback circuit

Currently, the last stage of the FB system includes the analog FB circuit. The FB circuit processes signals according to Eq. (1), and thus its amplitude must be constant. But as shown in Fig. 3 (a), the output signal of the analog FB

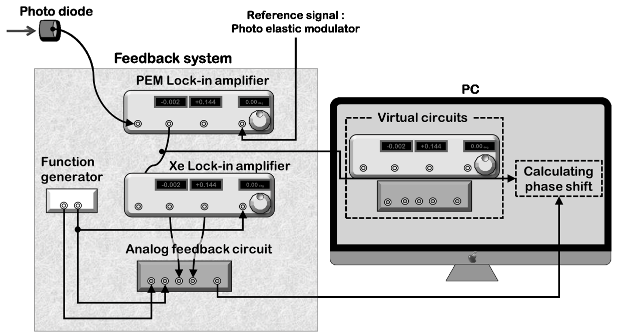

Figure 1: Feedback system which modulates, demodulates and amplifies the precession signal. The input signal to the Xe-LA and the output signal from the feedback circuit are used to calculate the phase shift.

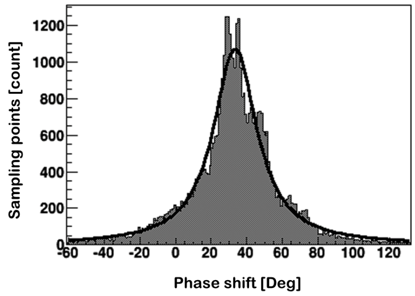

Figure 2: Histogram for the phase shift in the feedback system. Solid line indicates the result of fitting with a function of the Cauchy distribution.

circuit is found to show a beat-like ripple. The rippling may unintentionally interfere the ^{129}Xe precession, resulting in a frequency shift. The frequency shift $\Delta\nu$ due to the rippling is calculated as an average of pulling effects for the individual sample points:

$$\Delta\nu = \frac{1}{2\pi T_2 n}\sum_{i=1}^{n} \tan\delta_i \tag{3}$$

where n is the total number of sampling points, δ_i the phase difference for the i-th sampling point from the peak of the histogram. Measurements for 200 s was repeated 40 times. The frequency shift is caused by the circuit output asymmetry and is calculated for T_2 = 10 s as $\Delta\nu \sim 150\ \mu$Hz. Although $\Delta\nu$ might be reduced for longer measurement durations, the rippling needs to be reduced for the maser stabilization.

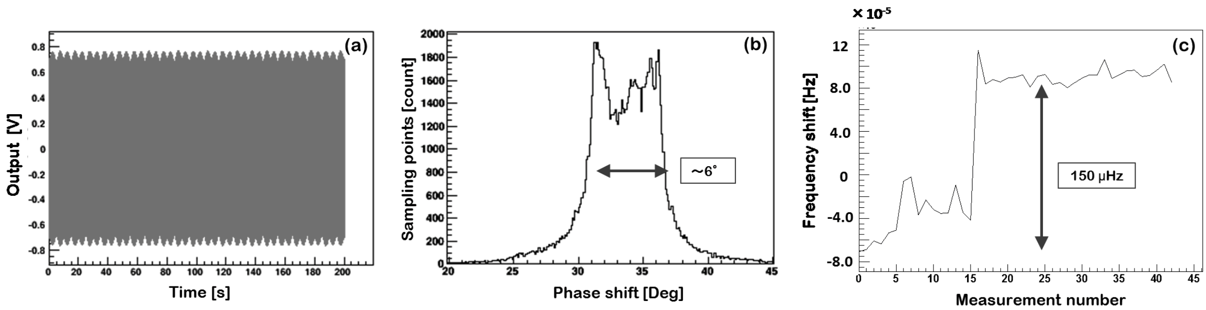

Figure 3: Output signal from the analog feedback circuit: (a) The output oscillates at the same frequency with the ^{129}Xe precession and has a slow beat-like ripple. (b) Calculation result of the phase shift in the circuit. (c) Pulling effect caused by the asymmetry of the output. The individual measurements were carried out for 200.

The output of the analog FB circuit was found to exhibit unwilling rippling. Such noises existing in the FB field would interfere the ^{129}Xe spin precession directly. In order to protect the ^{129}Xe precession from such noises, a CPU board implementing a digital FB circuit was introduced. The CPU board has the following main specifications: (i) Four analog-to-digital converters and one digital-to-analog converter take 10 μsec for a conversion. (ii) The CPU can work at a clock rate of 50 MHz. (iii) A complex programmable logic device enables us to program the circuit operation. The digital FB circuit is programed to process the input signals according to Eq. (1) in a single input/output cycle of 150 μs duration. The output from the digital FB circuit has no rippling as shown in figure 4(a). In the same way as in the analog FB circuit, the frequency shift caused by the circuit output asymmetry is calculated to be $\Delta\nu \sim 200$ nHz. Therefore the digital FB circuit is much less noisy compared to the analog one.

The ^{129}Xe maser was operated by using the digital FB system. The setup except for the FB system was the same as in Ref. [5]. The phase of $\boldsymbol{B}_{\mathrm{FB}}$ was determined based on the above procedure. We have succeeded in operating

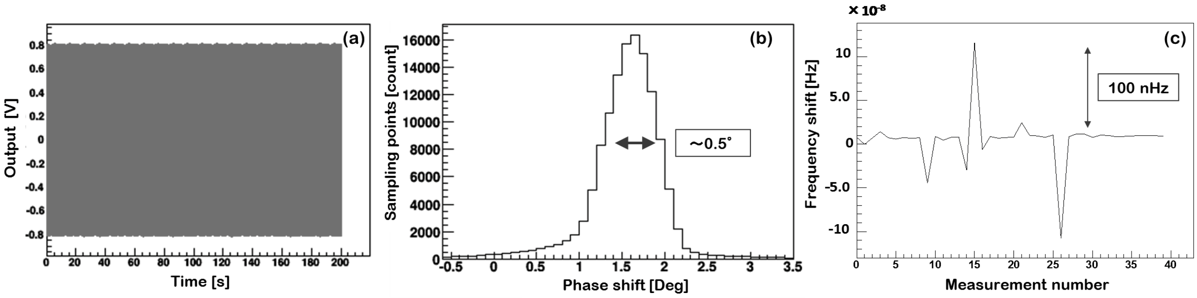

Figure 4: Output signal from the digital feedback circuit: (a) The output shows no beat-like ripple. (b) Calculation result of the phase shift in the circuit. (c) Pulling effect caused by the asymmetry of the output. The individual measurements were carried out for 200 sec

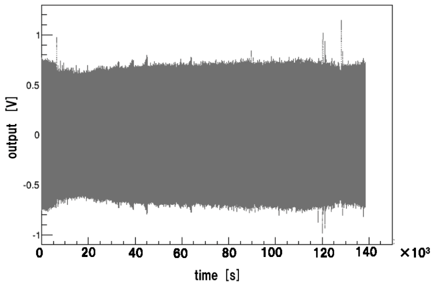

Figure 5: Maser oscillation signal using a digital feedback circuit. The ^{129}Xe maser was operated successfully.

the ^{129}Xe with the digital FB system, as shown in Fig. 5. The maser oscillation continued over one day without any unexpected interruption. Although a detailed analysis of the characteristics of the digital FB system is still in progress, the possibility to incorporate the digital FB system into the spin maser system for the EDM measurement has been demonstrated.

4. Summary

For the ^{129}Xe EDM measurement, an active nuclear spin maser is being developed. The spin maser undergoes a pulling effect due to phase errors in the FB field. Phase shifts in the FB system include those from unknown origins. The present analyses have revealed that the phase shifts arises in the two circuits in the FB system. The calculation of the phase shift allows us to control the $\boldsymbol{B}_{\rm FB}$ phase within 0.01° and reduces the pulling effect to 2.8 μHz or smaller.

The output of the analog FB circuit shows beat-like ripples which might interfere the maser operation. In a test experiment in which the analog FB circuit was replaced by the digital FB circuit, it was found that the noise of the digital FB circuit was negligible, in contrast to the analog FB circuit, and the frequency pulling effect stemming from the asymmetry of the output signal from the digital FB circuit is estimated to be 200 nHz. The ^{129}Xe maser was successfully operated using the digital FB system, in which new scheme of the phase determination was employed.

acknowledgments

This work was partly supported by the JSPS KAKENHI (No.21104004 and No.21244029). One of the authors (T. Sato) would like to thank the JSPS Research Fellowships for Young Scientists for the support.

References

[1] M. A. Rosenberry *et al.*, Phys. Rev. Lett. **86**, 22 (2001).
[2] A. Yoshimi *et al.*, Phys. Lett. A **304**, 13 (2002).
[3] A. Yoshimi *et al.*, Phys. Lett. A **376**, 1924 (2012).
[4] T. Inoue *et al.*, Physica E **43**, 847 (2011).
[5] T. Sato *et al.*, Proceedings of FPUA2014 (this proceedings).